Challenges of NDE Simulation Tool Development and Validation For Composites

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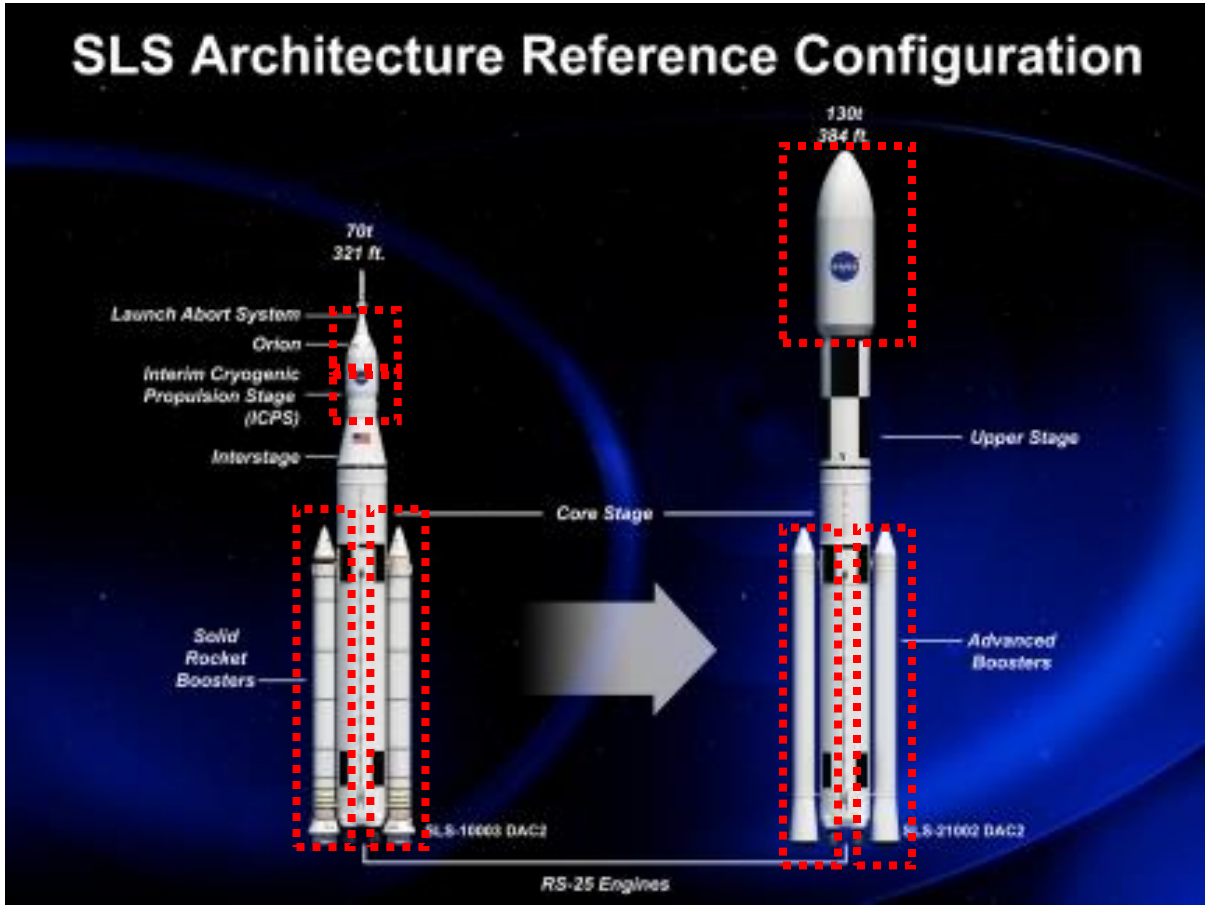
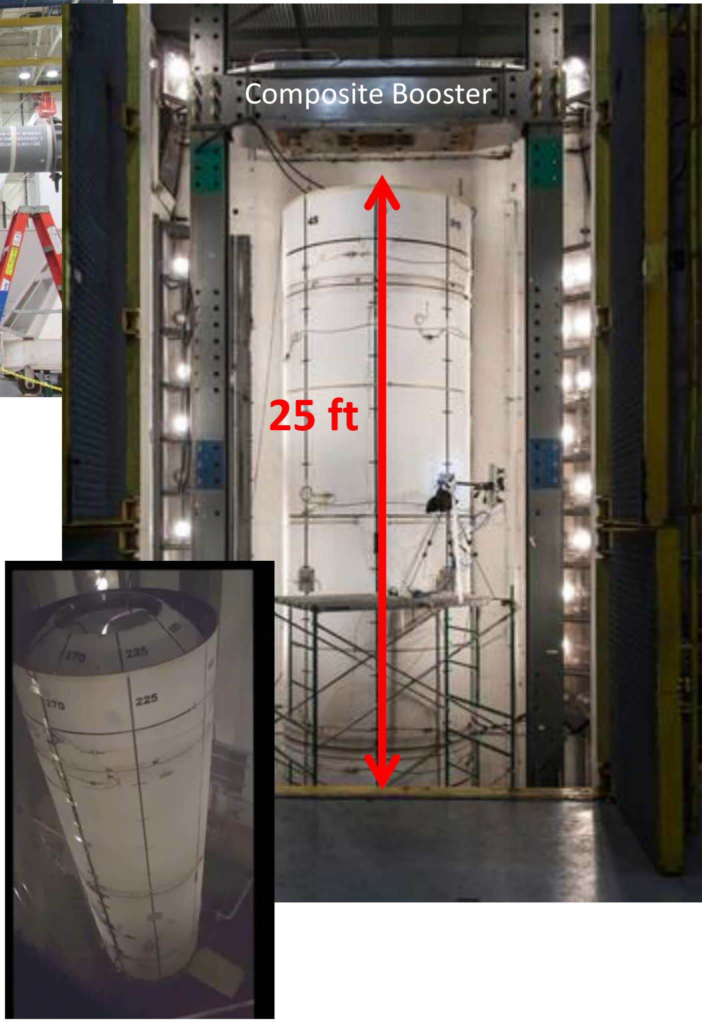
Overview

- Focus on composites
- Validation related challenges
  - Experimental comparisons
  - Avoiding application of the tool to cases that don't fit prior validations
- Tool development challenges
  - Memory efficiency
  - Computational efficiency (speed)
  - Hardware related challenges
    - Hardware selection and keeping up with continuous progress

Composites for Space

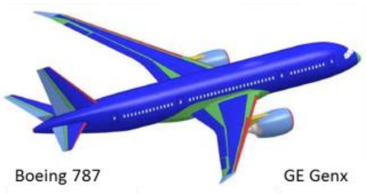


https://www.youtube.com/watch?v=IRutJfOsglI



Composites for Aeronautics

- Advanced Composite Project (5 Year Project):
  - Reduce timeline for certification of composite structures
  - Partnership: NASA, FAA, DoD, Industry, University
- Rapid Inspection Technical Challenge:
  - Focus areas:
    - Inspection of complex geometry components
    - Rapid large area inspection
    - Damage/defect characterization
    - Validation of detectability
  - Damage types:
    - Microcracking, fiber waviness, delamination, porosity
- Simulation:
  - Enables model based inspection prediction/validation and cost effective method optimization
  - Custom code, 3D ultrasound simulation under development

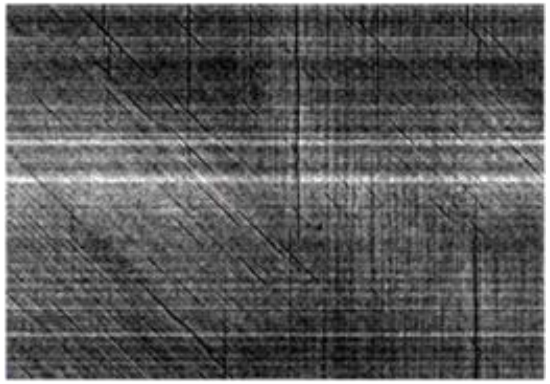


Lockheed Martin F-35

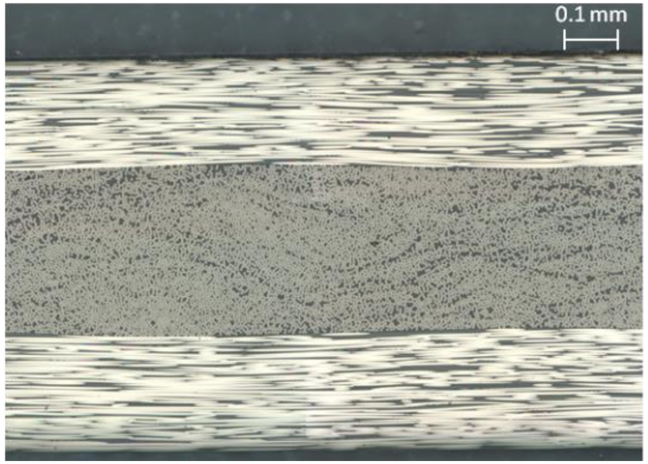
Northrop Grumman Fire Scout

Composite Damage/Defect Types

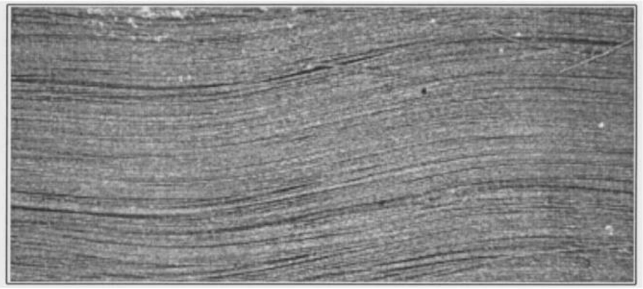
X-ray CT data of
microcrack damage



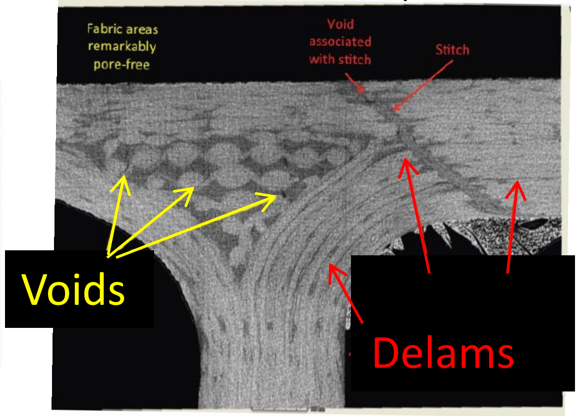
Micrograph showing resin rich
regions and fiber misalignment



Fiber waviness (in-plane),
From Kugler and Moon 2002
doi: 10.1177/0021998302036012575

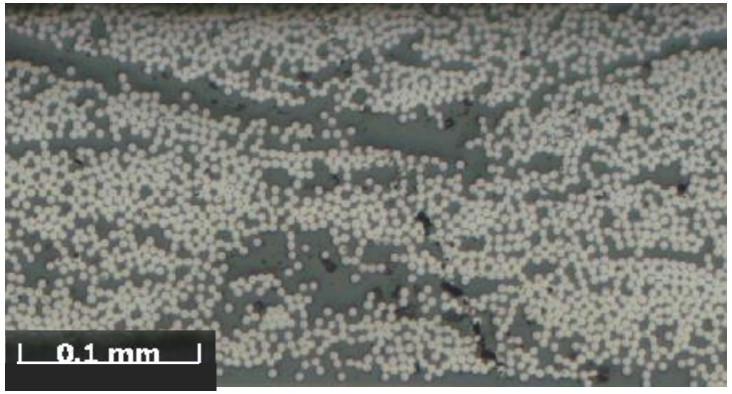


X-ray CT of PRSEUS Joint
From NASA TM-2013-217799 by Patrick Johnston

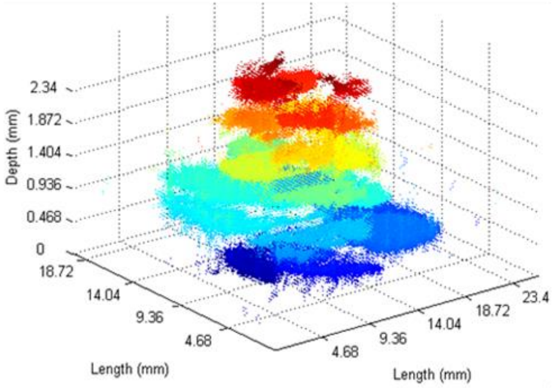


X-ray CT data of
microcrack damage

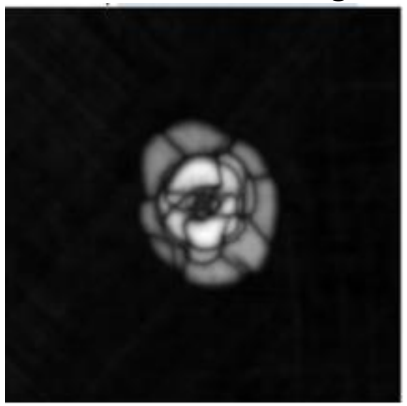
Micrograph showing porosity



X-ray CT data of
delamination damage



UT data of
delamination damage



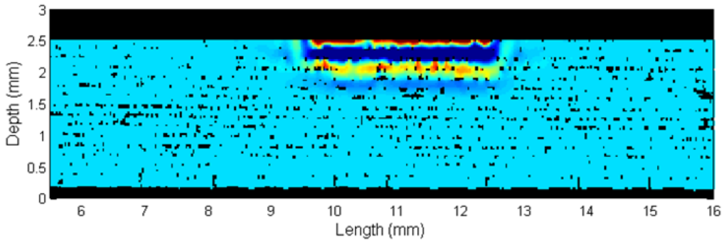
Simulation Tool Validation Challenges

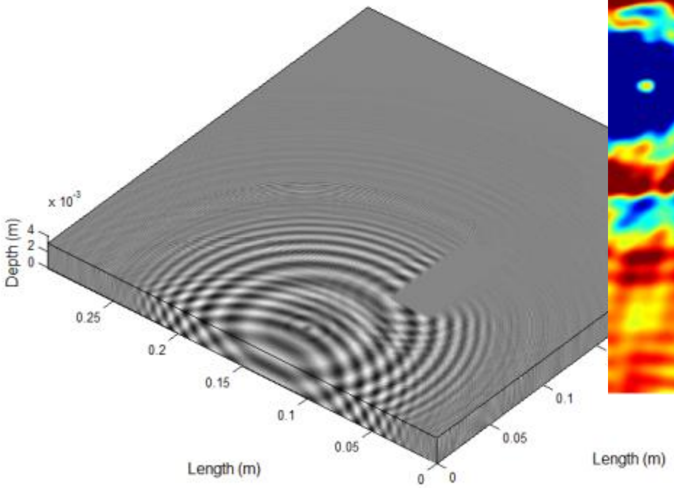
- Direct comparisons between simulation and experiment can be challenging
  - Requires specific experimental design
- Experimental case will always have some differences from the simulated case
- Getting representative samples for experiment can be a challenge
  - Creating representative defects/damage
  - Differences between ‘idealized’ material properties and as-manufactured
- Must perform re-validation against appropriate cases when the simulation tool is used for a new purpose
  - Understanding of the physics is required to know when this is necessary

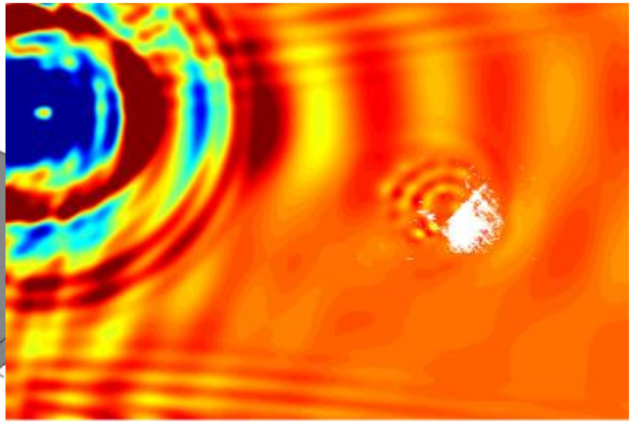
Example: Ultrasound simulation

Nondestructive Evaluation Sciences Branch

- Elastodynamic finite integration technique ultrasonic simulation code
  - Custom C++ and MPI
  - Similar to finite difference
  - Adaptable, efficient, all details under our control

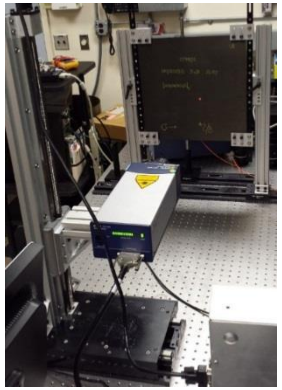




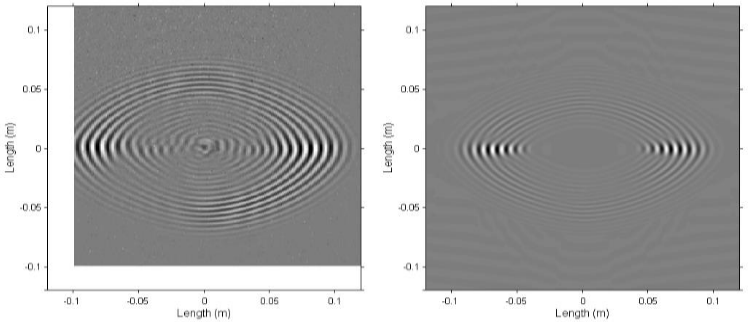


Simulation Validation Approach 1

- Laser Doppler vibrometry experiment comparisons
- Group velocity comparisons unidirectional IM7/8552 8-ply sample:
  - Track envelope peak propagation (using Hilbert transform)

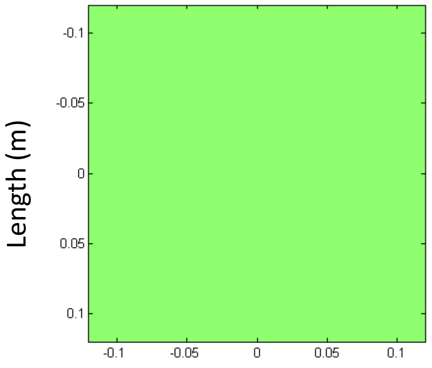


Approximate time=56 microseconds after initial

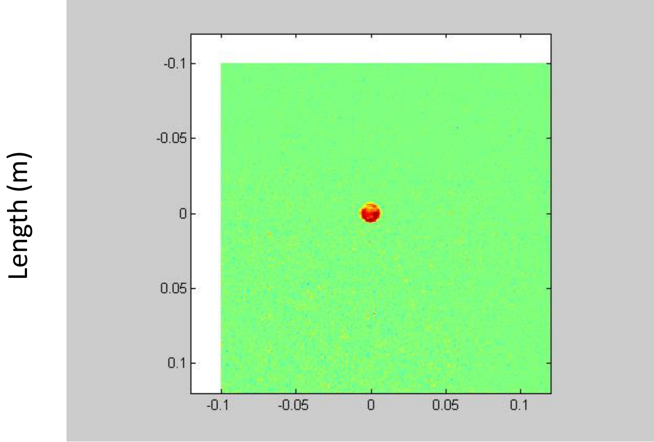


a) LV wavefield data b) EFIT result

EFIT simulation result



Experimental LV wavefield data



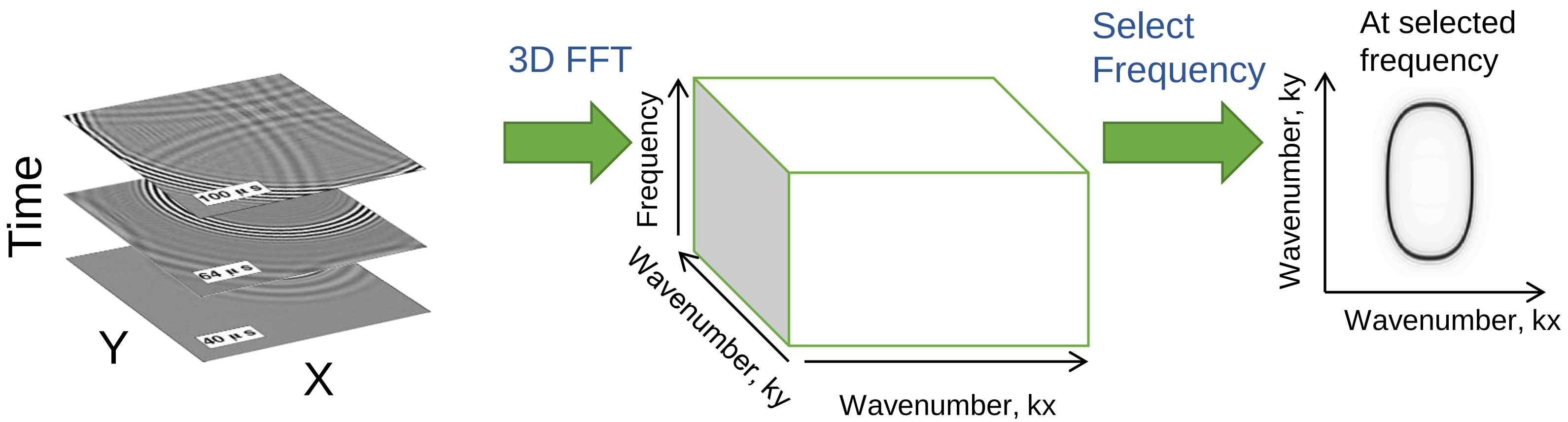
Note: time step of frames and colormapping in the two movies is not the same

Mode 1 group velocity comparisons:

Method	Mode 1, 0° v_g(m/s)	Mode 1, 90° v_g (m/s)	% Difference from EFIT, 0°	% Diff from EFIT, 90°
EFIT	1956 +/− 90	1335 +/− 44	–	–
Dispersion curves	1911	1254	2.33	6.26
Experiment	2254 +/− 84	1464 +/− 69	14.16	9.22

Simulation Validation Approach 2

- Compare wave behavior in all directions
- Wavenumber comparison technique:
  - Start with data for all grid points on surface of sample, amplitude at x-position vs. y-position vs. time
  - Take 3D FFT to yield x-wavenumber vs. y-wavenumber vs. frequency (where $k=f/c_{phase}$)
  - Select frequency slice that corresponds to the excitation frequency

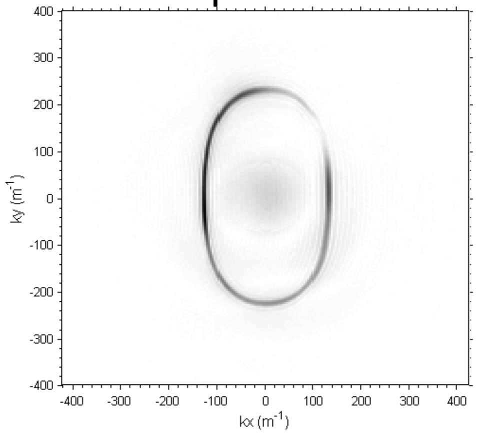


Unidirectional Case

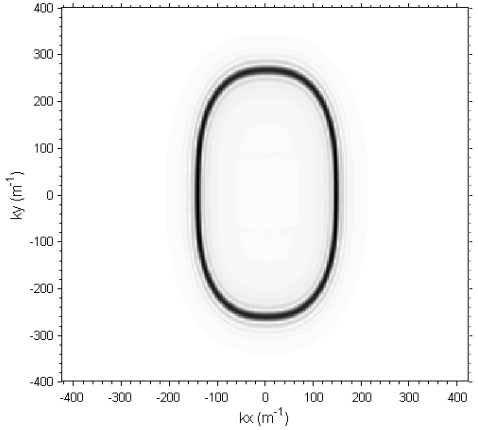
- A0 mode results (S0 mode is very low amplitude)
- Amplitude variation around k_x-k_y oval is due to excitation source filtering (changes with couplant, transducer, etc and can be included in EFIT as well)
  - Interested in directional wave behavior observed via wavenumber values

Wavenumber plots

Experiment



Simulation



Unidirectional laminate: Mode 1 wavenumber comparisons

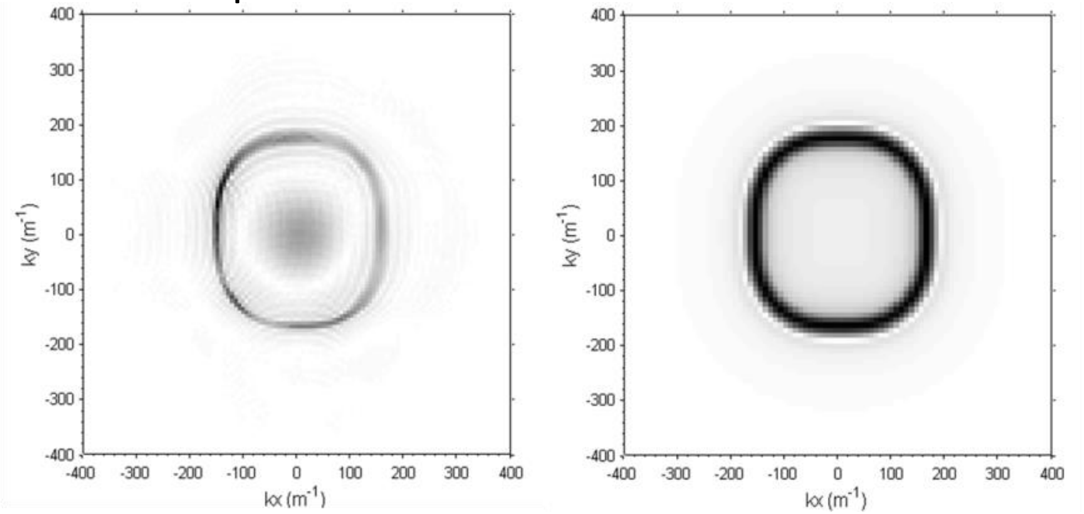
Method	0° $k(1/m)$	90° $k(1/m)$	% Difference from EFIT, 0°	% Diff from EFIT, 90°
EFIT	143.3	263.4	–	–
Dispersion curves	139.7	258.1	2.54	2.03
Experiment	129.5	229.1	10.12	13.93

Cross-ply case

- Demonstrates ability to build up laminates ply-by-ply in EFIT
- However - is orthotropic only!

$[0/90]_{2s}$

Experiment   Simulation



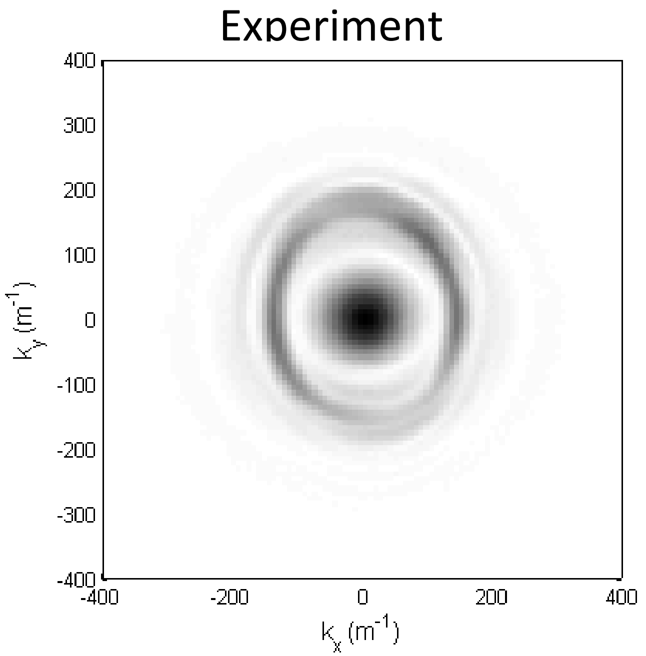
$[0/90/0/90]_s$ Layup				
Method	0° $k(1/m)$	90° $k(1/m)$	% Difference from EFIT, 0°	% Diff from EFIT, 90°
EFIT	159.8	169.2	–	–
Dispersion curves	161.4	180.7	1.00	6.57
Experiment	152.3	170.5	4.81	0.77

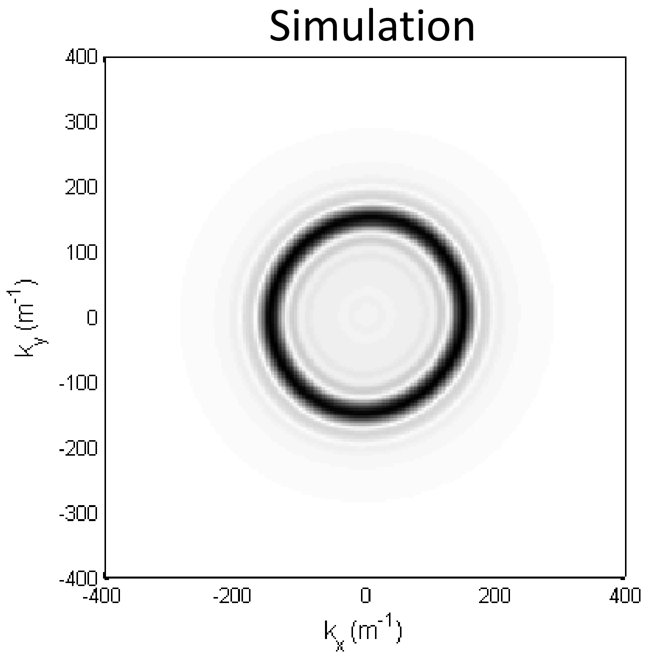
Orthotropic vs. Non-orthotropic

$$T_{11}^{(t+\Delta t/2)} = T_{11}^{(t-\Delta t/2)} + \frac{\Delta t}{\Delta x}\left[c_{11}^{(n)}\left(v_1^{(n)} - v_1^{(n-\hat{x}_1)}\right) + c_{12}^{(n)}\left(v_2^{(n)} - v_2^{(n-\hat{x}_2)}\right) + c_{13}^{(n)}\left(v_3^{(n)} - v_3^{(n-\hat{x}_3)}\right)\right]$$

$$\begin{aligned}
T_{11}^{(t+\Delta t/2)} = T_{11}^{(t-\Delta t/2)} &+ \frac{\Delta t}{\Delta x}\left[c_{11}^{(n)}\left(v_1^{(n)} - v_1^{(n-\hat{x}_1)}\right) + c_{12}^{(n)}\left(v_2^{(n)} - v_2^{(n-\hat{x}_2)}\right) + c_{13}^{(n)}\left(v_3^{(n)} - v_3^{(n-\hat{x}_3)}\right)\right] \\
&+ \frac{\Delta t}{4\Delta x}\Big[c_{14}^{(n)}\Big(\left(v_2^{(n)} + v_2^{(n-\hat{x}_2)} + v_2^{(n+\hat{x}_3)} + v_2^{(n-\hat{x}_2+\hat{x}_3)}\right) \\
&-\left(v_2^{(n-\hat{x}_2)} + v_2^{(n)} + v_2^{(n-\hat{x}_2-\hat{x}_3)} + v_2^{(n-\hat{x}_3)}\right) + \left(v_3^{(n-\hat{x}_3)} + v_3^{(n)} + v_3^{(n+\hat{x}_2-\hat{x}_3)} + v_3^{(n+\hat{x}_2)}\right) \\
&-\left(v_3^{(n-\hat{x}_3)} + v_3^{(n)} + v_3^{(n-\hat{x}_2-\hat{x}_3)} + v_3^{(n-\hat{x}_2)}\right)\Big) \\
&+c_{15}^{(n)}\Big(\left(v_1^{(n-\hat{x}_1)} + v_1^{(n)} + v_1^{(n-\hat{x}_1+\hat{x}_3)} v_1^{(n+\hat{x}_3)}\right) - \left(v_1^{(n-\hat{x}_1)} + v_1^{(n)} + v_1^{(n-\hat{x}_1-\hat{x}_3)} + v_1^{(n-\hat{x}_3)}\right) \\
&+\left(v_3^{(n-\hat{x}_3)} + v_3^{(n)} + v_3^{(n+\hat{x}_1-\hat{x}_3)} + v_3^{(n+\hat{x}_1)}\right) - \left(v_3^{(n-\hat{x}_1-\hat{x}_3)} + v_3^{(n-\hat{x}_1)} + v_3^{(n-\hat{x}_3)} + v_3^{(n)}\right)\Big) \\
&+c_{16}^{(n)}\Big(\left(v_1^{(n-\hat{x}_1)} + v_1^{(n-\hat{x}_1+\hat{x}_2)} + v_1^{(n)} + v_1^{(n+\hat{x}_2)}\right) - \left(v_1^{(n-\hat{x}_1-\hat{x}_2)} + v_1^{(n-\hat{x}_1)} + v_1^{(n)} + v_1^{(n-\hat{x}_2)}\right) \\
&+\left(v_2^{(n-\hat{x}_2)} + v_2^{(n)} + v_2^{(n+\hat{x}_1-\hat{x}_2)} + v_2^{(n+\hat{x}_1)}\right) - \left(v_2^{(n-\hat{x}_1-\hat{x}_2)} + v_2^{(n-\hat{x}_1)} + v_2^{(n-\hat{x}_2)} + v_2^{(n)}\right)\Big)
\end{aligned}$$

Quasi-isotropic case





[0/45/-45/90]s

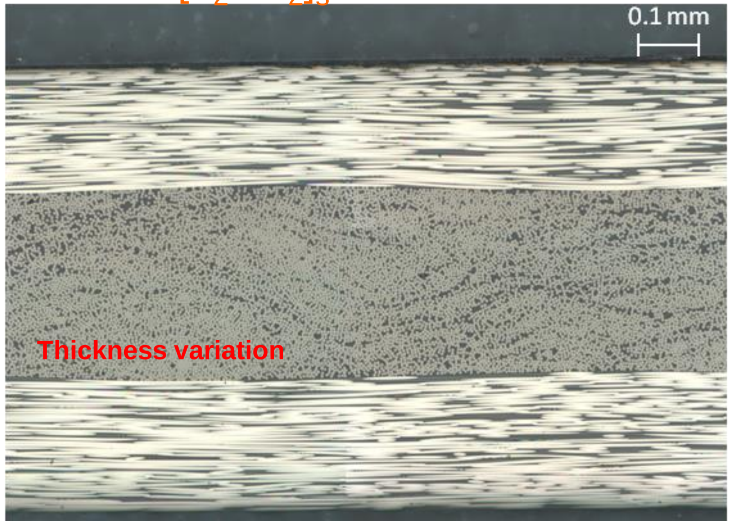
Method	kx, 0˚ (A mode)	ky, 90˚ (A mode)	% Diff EFIT 0˚	% Diff EFIT 90˚
EFIT	147.5	150.4	--	--
Experiment	140.6	166.1	4.68	10.44

*Ongoing work

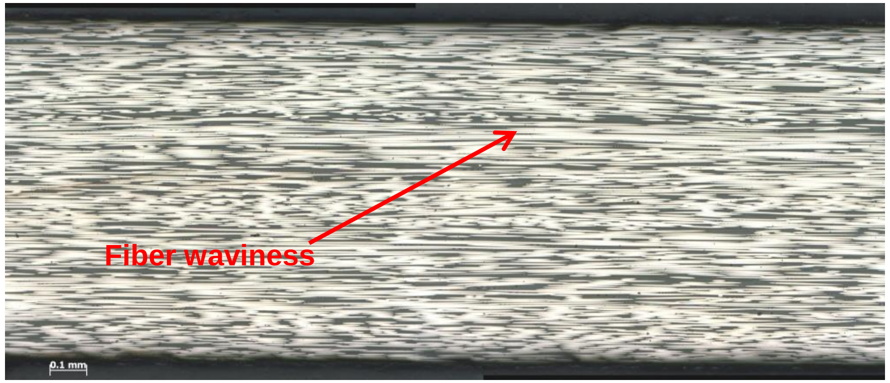
Differences from Experiment

- Overall simulation yields results close to experiment and predicted dispersion curves
- Expected some differences from experiment due to as-fabricated material properties of laminate versus “ideal” properties used in model
  - Thickness variation, fiber warping, variation in fiber density, slightly off-angle ply layers (laid up by hand)

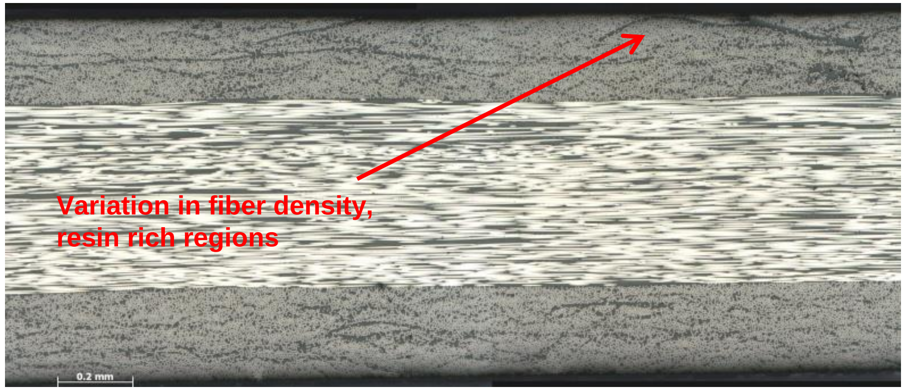
$[0_2/90_2]_s$ laminate:



Unidirectional laminate:



$[0_2/90_2]_s$ laminate:



Once we have a working simulation tool – let's use it!

- Develop optimized and new damage quantification methods
- Predict inspectability
- Validate SHM
- Etc…..

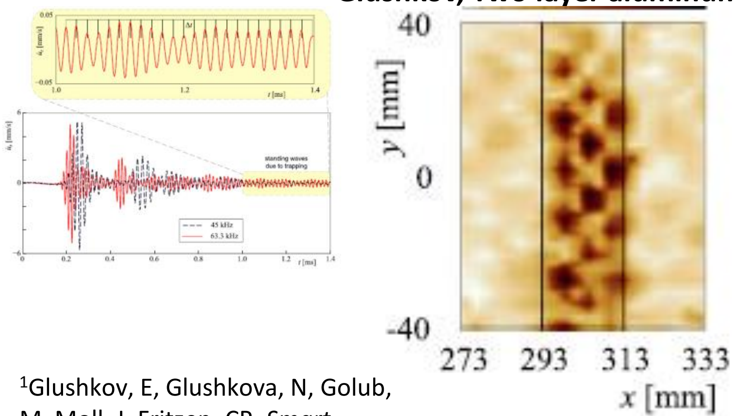
- Still have validation challenges ahead
- You developed a promising new inspection methodology, now go back and validate against experiment

Guided Wave Energy Trapping

Nondestructive Evaluation Sciences Branch

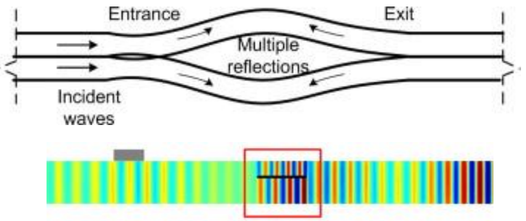
- Studied previously by several authors via LDV and simple simulations
  - These prior studies focused on single layer delamination

Glushkov, Two layer aluminum



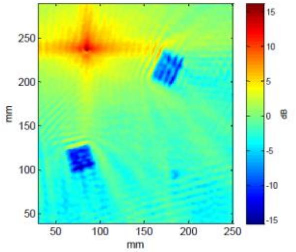
[1]Glushkov, E, Glushkova, N, Golub, M, Moll, J, Fritzen, CP. *Smart Materials and Structures* 21.12 (2012): 125001.

Sohn, Composite, single delam



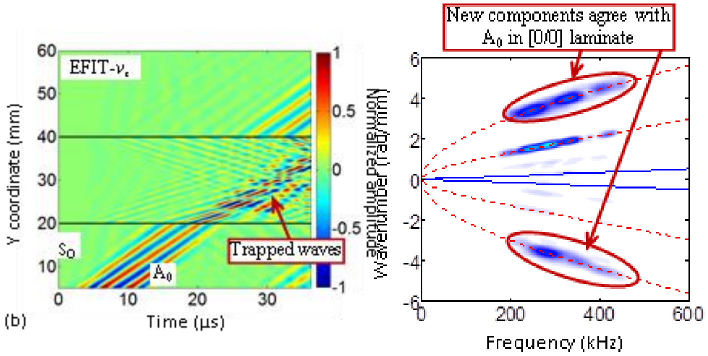
[2]Sohn, H., Dutta, D., Yang, J. Y., Park, H. J., DeSimio, M., Olson, S., & Swenson, E. (2011). *Composites science and technology*, *71*(9), 1250-1256.

Michaels, Composite, simulated single delam



Michaels , J; Dawson, A ; Michaels, T ; Ruzzene, M. Proc. SPIE 9064, (2014); doi:10.1117/12.2045172.

Tian, Composite, single delam

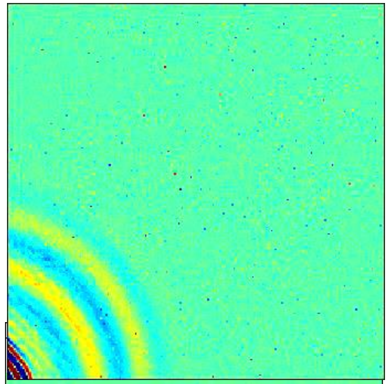


[3]Zhenhua Tian ; Lingyu Yu ; Cara A. C. Leckey; Proc. SPIE 9063, (2014), doi:10.1117/12.2044927.

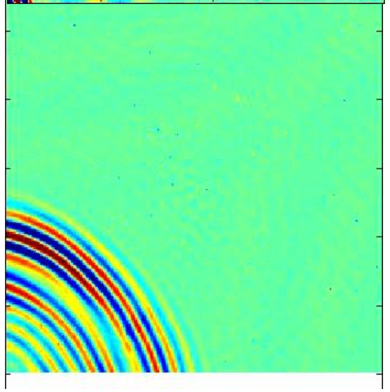
Energy Trapping

- Potential for rough sizing of damage via rapid data processing

LDV data:
500 kHz

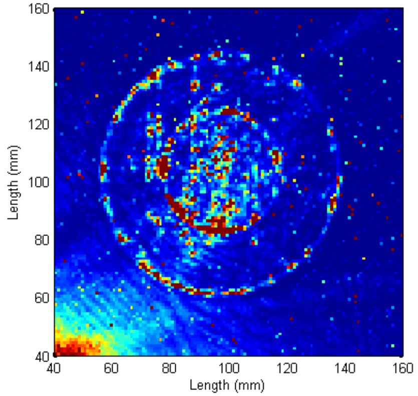


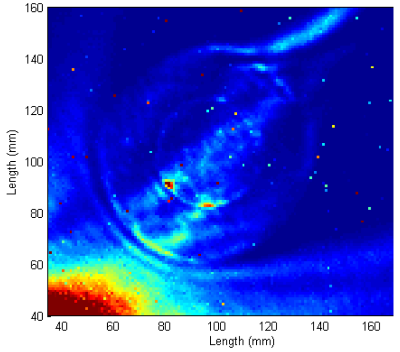
LDV data:
200 kHz

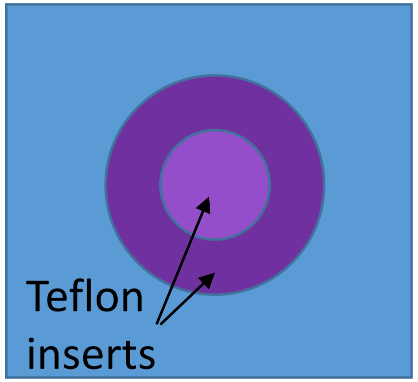


Mass normalized cumulative energy

$$E_i(x,y,z,t) = \int_{t_1}^{t_2} \frac{1}{2} v_i{}^2 dt$$



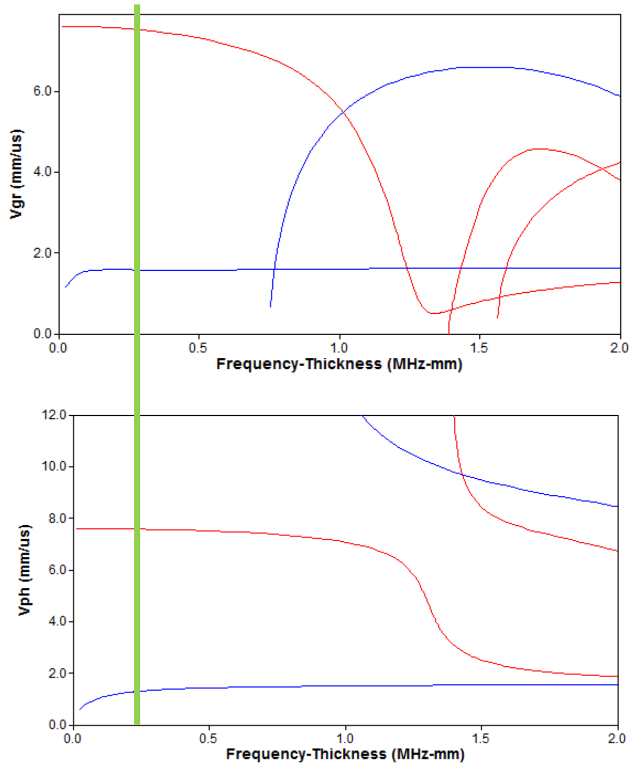


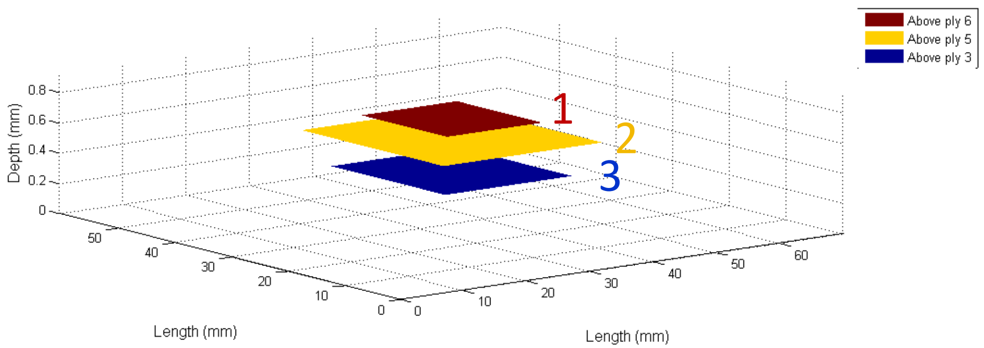


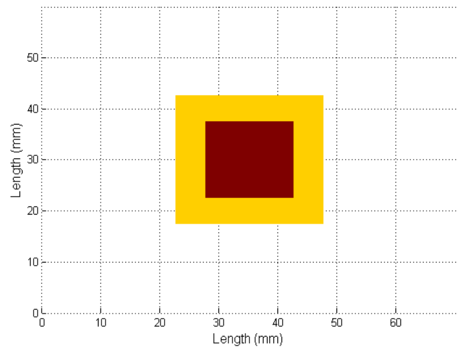
- Can energy trapping be leveraged for multi-ply delam characterization with only single sided access?

Hidden Delamination Study

- Specifically: can energy reduction be used to provide information about the presence of hidden delamination damage?
- Simulation based study:
  - 8 ply, IM7/8552 CFRP sample $[(0/90)_2]_s$, 0.92 mm thick
  - 3 simple delamination cases: 1, 2, and 3 delaminations (+ pristine case)
  - 300 kHz, 3 cycle Hann windowed sine wave
  - dx=19 µm, dt analysis = 0.29 µs (dt/200)

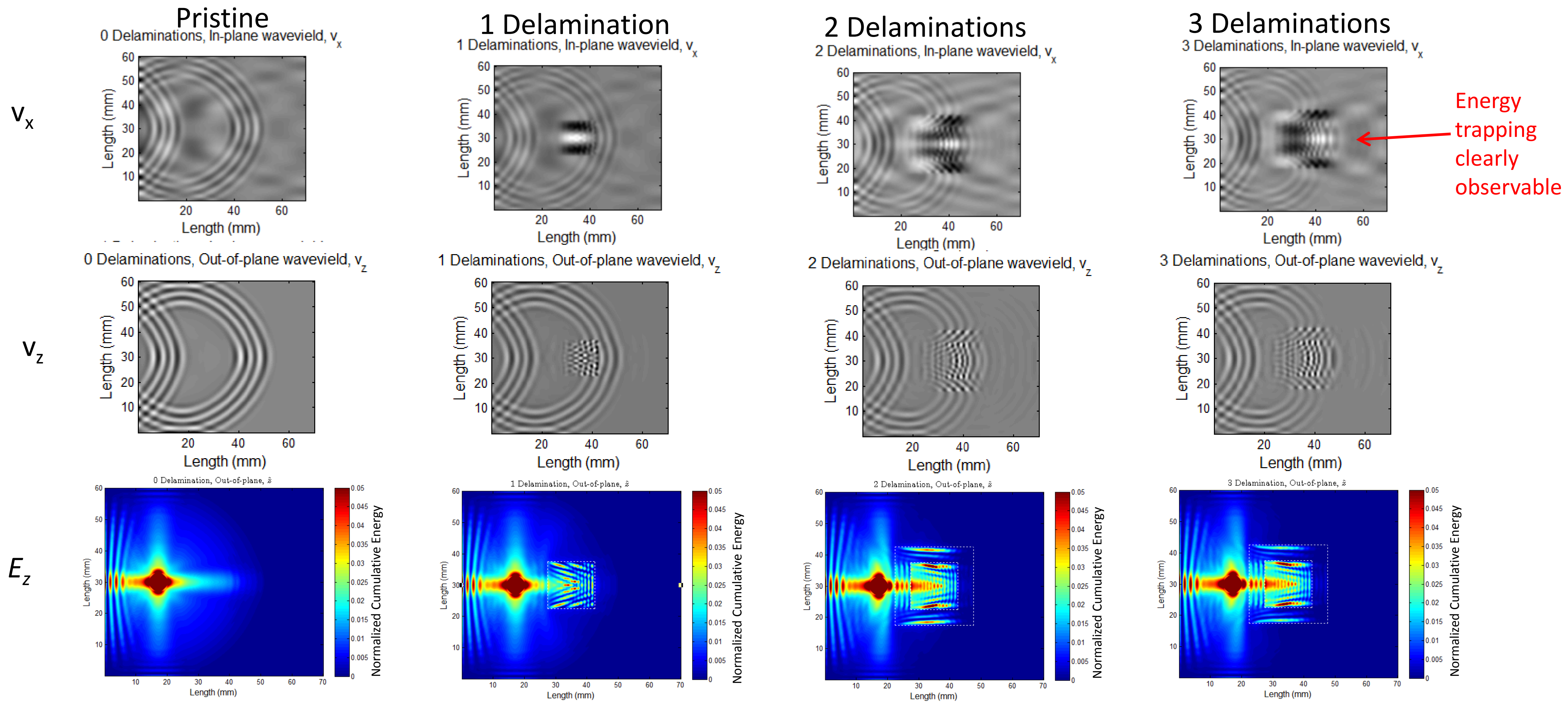






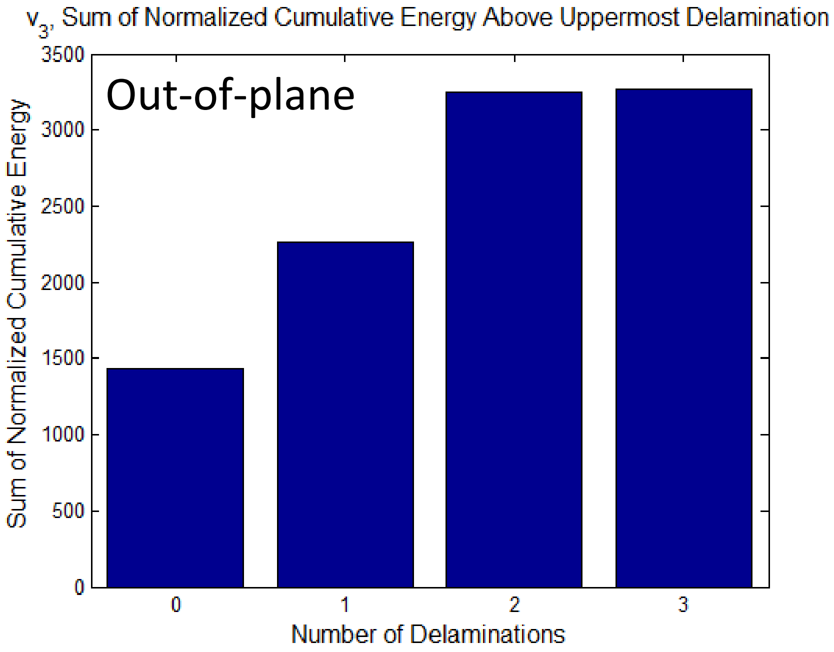
Simulation Study: Cumulative Energy

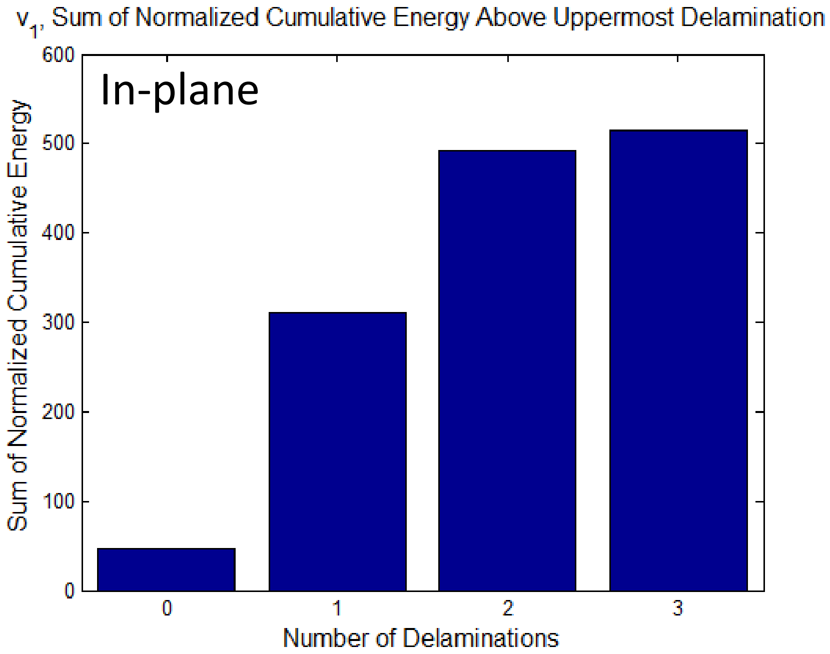
Nondestructive Evaluation Sciences Branch



Energy trends

- Quantitative comparisons, energy above top delamination



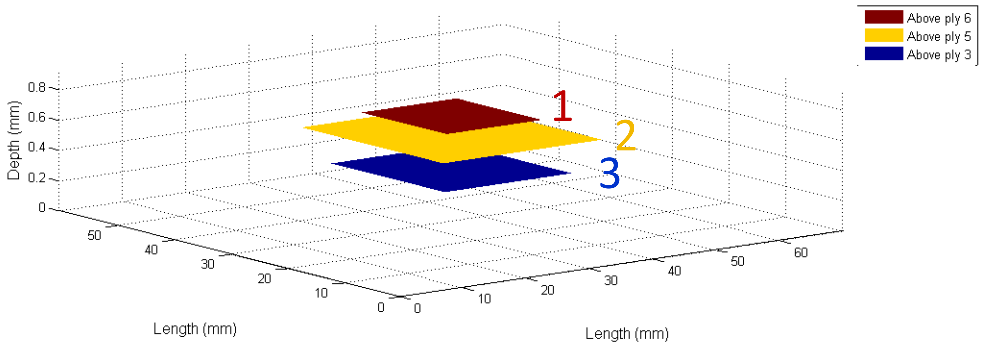


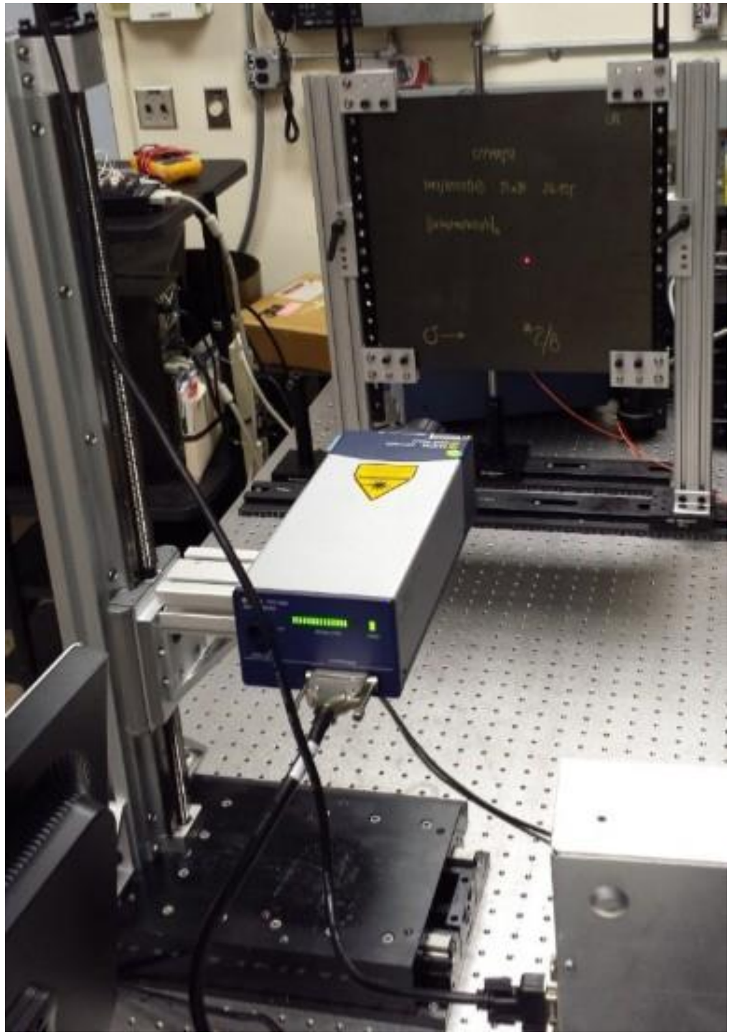
Note: nonzero for pristine because energy still passes into that region (especially with edge scattering, etc)

Validation

Nondestructive Evaluation Sciences Branch

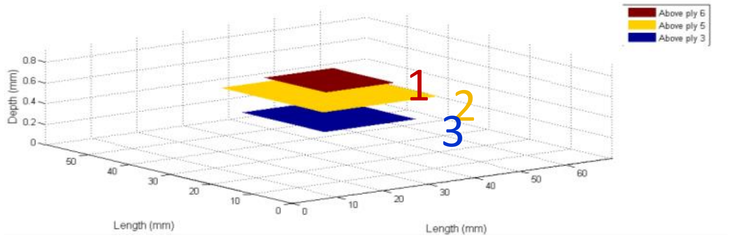
- LDV scans of composites with Teflon inserts
- Matching simulated cases (ranging from single delam to 3)
- Contact transducer for excitation
- Plan is to measure cumulative energy trapping

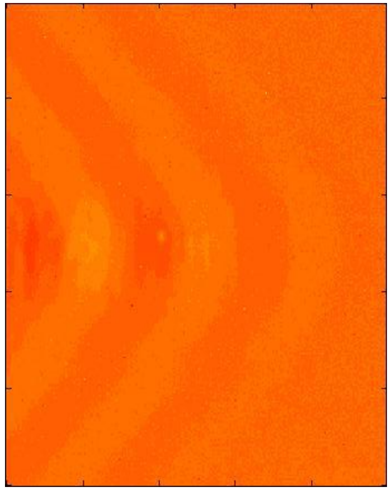




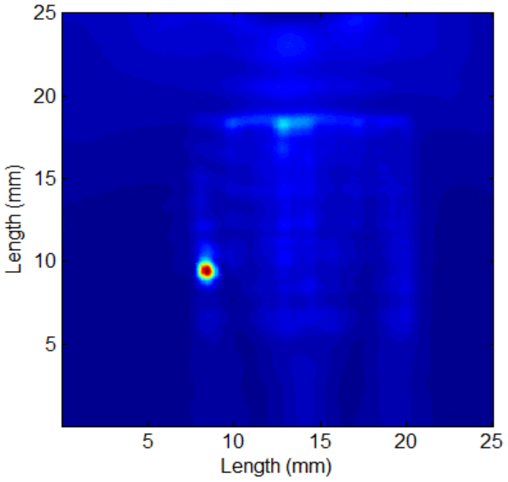
Inclusion with Teflon Case

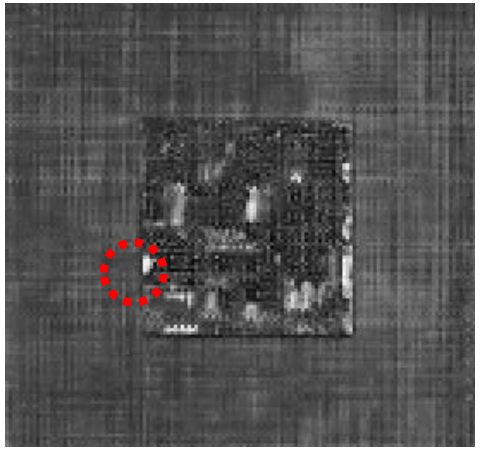
- Unexpected defects/variability due to manufacturing
- Immersion UT 10 MHz, 0.01” resolution



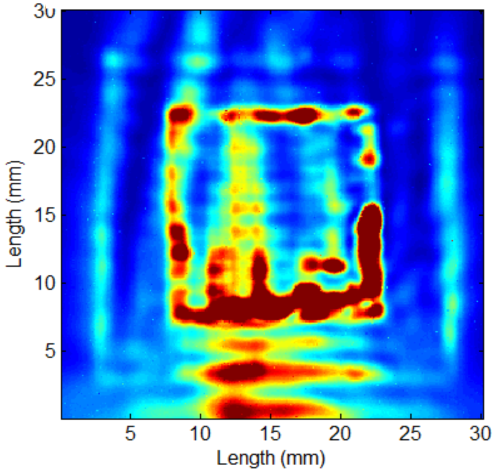


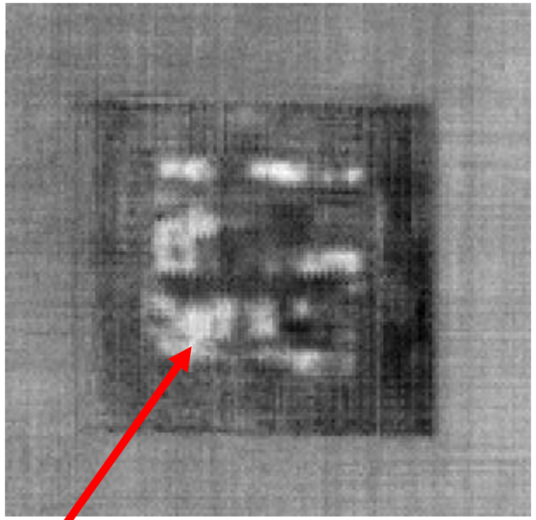
1 Delamination Case





2 Delamination Case



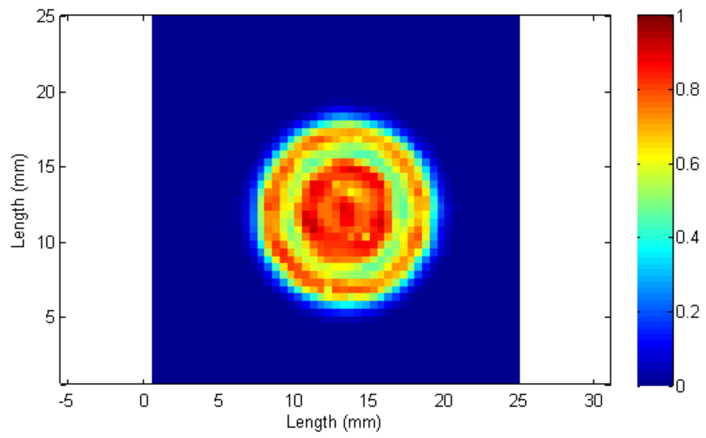


Resin rich regions? Wrinkles?

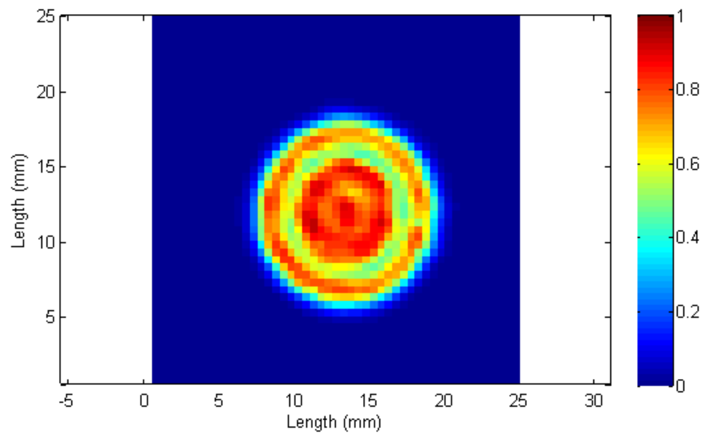
Repeatability

- For amplitude based studies, repeatability can be an issue
- Differences between repeated data scan sets
    - Couplant changes!
- Also, planning to use laser excitation

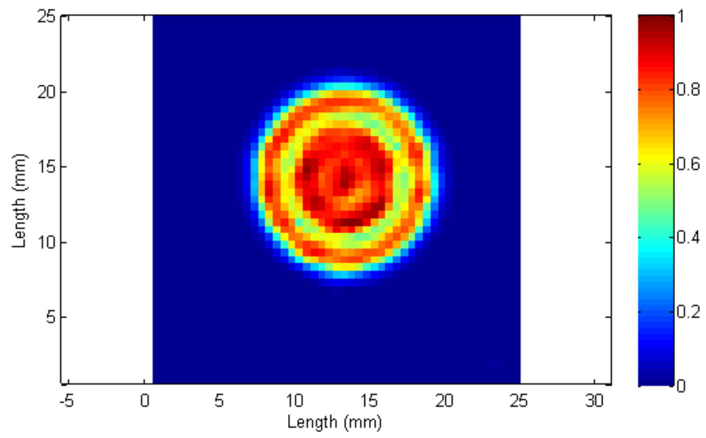
Transducer face: Scan 1



Transducer face: Scan 2



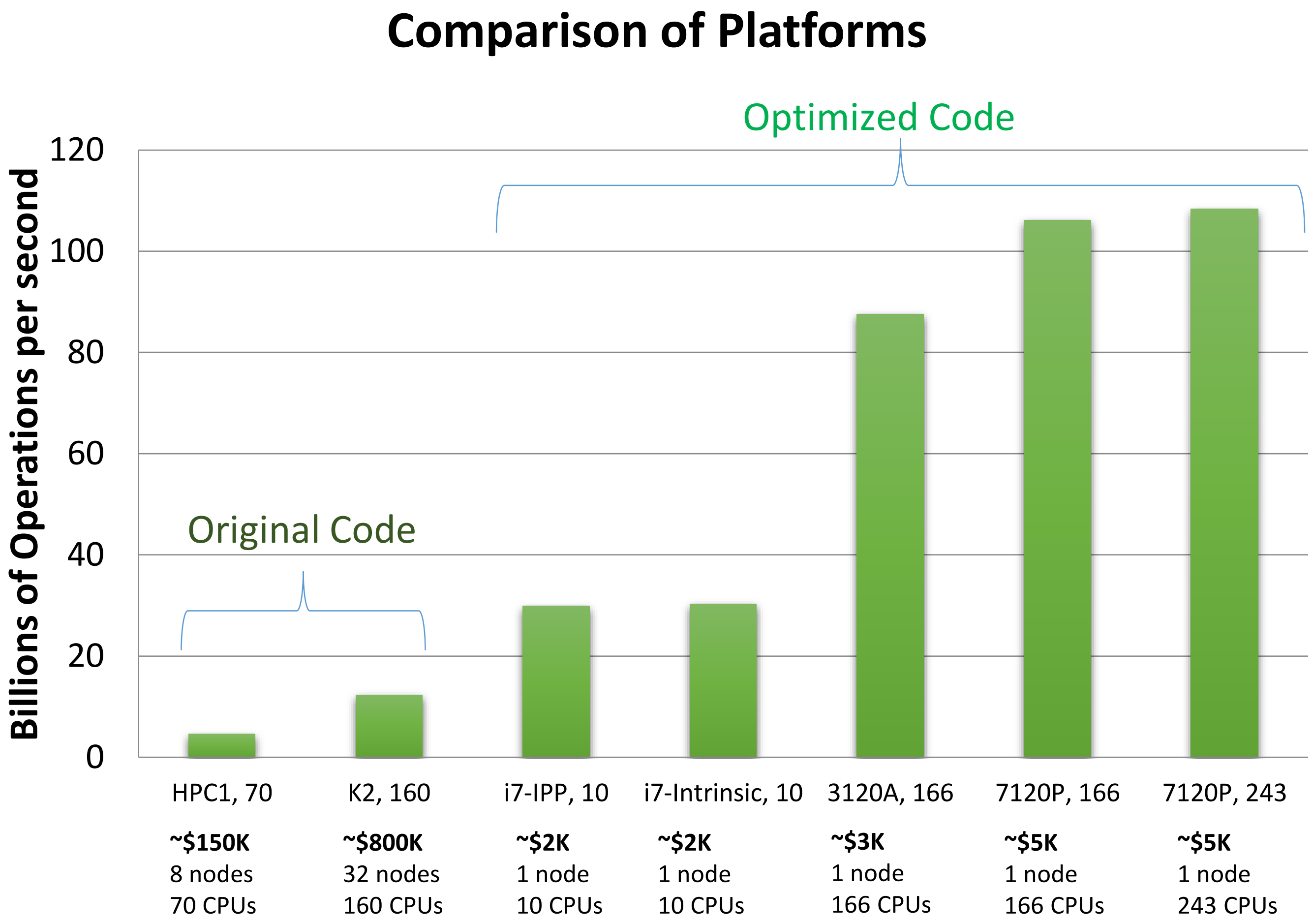
Transducer face: Scan 3



Code optimization

Nondestructive Evaluation Sciences Branch

- Single vs double precision?
- Porting code often requires some amount of re-writes
- Must check that ported code yields same results as validated code!
- Example shown here:
  - ~10x improvement in efficiency
  - 0.6% cost
- But – scalability also matters



Conclusions

- Inevitable shift towards more use of modeling and simulation to test hypotheses, optimize methods, predict inspectability, etc
- This is a good thing, as it may enable new approaches and cost-effective investigation of inspection methods
- However, validation is a key step with many challenges
- Whether custom or commercial simulation software is used, it is of key importance to know that validation has been performed and successful

Thanks to: Eric Burke, NASA LaRC

END